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TECHNICAL MEMORANDUM

X-334

REVIEW OF TECHNIQUES APPLICABLE TO THE RECOVERY

OF LIFTING HYPERVELOCITY VEHICLES

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TECHNICAL MEMORANDUM X-334

REVIEW OF TECHNIQUES APPLICABLE TO THE RECOVERY OF LIFTING HYPERVELOCITY VEHICLES*

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SUMMARY

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A general review of piloting problems concerned with the recovery phase of lifting hypervelocity vehicles is presented. A short discussion is offered pertinent to the maneuvering capabilities and piloting techniques applicable to the initial approach phase of gliders with low lift-drag ratios. The principal emphasis concerns factors affecting the final approach and landing operation of these gliders. The results of general flight studies as well as recent experience obtained in the approach and landing of the X-15 research airplane are reviewed. Finally, a definition of the limits of piloted flared landings is developed.

In regard to the final approach and landing phase, the more conventional circular pattern and the straight-in approach each had merits that were appreciated by the pilots. The conventional pattern afforded somewhat more flexibility of operation in space positioning prior to the flare, whereas the straight-in approach had the advantage of alleviating pilot-judgment requirements during the flare.

Although there have been a number of problems encountered in X-15 landing operations, the present procedure of a relatively high-speed, circular approach with gear and flap extension delayed until completion of the flare is providing entirely satisfactory landings.

Flight experience has been obtained with vehicles that should have landing characteristics similar to many of the possible future winged reentry vehicles. In general, a usable lift-drag ratio of 3.5 or higher should provide the pilot with fair-to-good landing characteristics and allow a speed flexibility that lends itself to a choice of techniques.

There is strong reason to believe that, regardless of technique, a lift-drag ratio in the flare of approximately 2.5 may represent a practical lower limit for piloted flared landings.

*Title, Unclassified.

INTRODUCTION

Piloting problems concerned with the recovery phase of lifting hypervelocity vehicles as defined in figure 1 are considered in this paper. The reentry is assumed to be completed at a Mach number of 5 and at 100,000 feet.

A brief discussion is presented relative to the maneuvering capabilities and piloting techniques applicable to the initial approach phase of gliders with low lift-drag ratios. The principal emphasis of this paper, however, is on the final approach and landing operation of such vehicles. The results of general flight studies as well as recent experience obtained in the approach and landing of the X-15 research airplane are reviewed. Finally, a definition of the limits of piloted flared landings is presented.

It should be noted from the outset that, although the use of advanced energy management and automatic landing systems may have an important role in future operations of advanced vehicles, such devices are not considered in this paper, inasmuch as the primary interest was in establishing base line piloting capabilities obtainable with a minimum of guidance aids.

SYMBOLS

g	acceleration due to gravity, ft/sec^2
h	altitude, ft
L/D	lift-drag ratio
$(L/D)_{max}$	maximum lift-drag ratio
M	Mach number
n	normal load factor based on weight of 14,000 pounds
t^*	time between completion of flare and minimum touchdown speed, sec
V_i	indicated airspeed, knots
$(V_i)_{TD}$	indicated airspeed at touchdown, knots

V_v	vertical velocity, ft/sec
W/S	wing loading, lb/sq ft
α	angle of attack, deg
γ	flight-path angle, deg
γ_0	flight-path angle at flare initiation, deg
δ_h	horizontal-stabilizer deflection, deg

Subscripts:

I,III	phase of landing technique

INITIAL APPROACH

Figure 2 shows the maneuverability envelope during the initial-approach phase of a reentry vehicle as determined from simulator tests. Data are presented for the X-15 configuration, which has an average maximum lift-drag ratio $(L/D)_{max}$ of 2.5 in the lower supersonic speed range. The initial conditions are assumed to be a Mach number of 5 at an altitude of 100,000 feet. The maneuverability limits defined were obtained by performing constant bank-angle turns until a desired heading was obtained and then flying near $(L/D)_{max}$ until a point 30,000 feet over the landing site was reached. For maximum-range considerations the optimum bank angle is a function of the required heading change. It is seen that the lateral-maneuverability potential is slightly greater than 100 nautical miles and the longitudinal range is somewhat over 200 nautical miles. To obtain some appreciation for the ranging problems and to define optimum techniques, simulated visual-flight-rule (VFR) and ground-controlled-approach (GCA) runs were made to representative landing sites at various locations within the envelope. The least difficult navigational problems occurred in the unshaded region A. In this area, range control could be easily obtained by speed-brake modulation. Speed brakes were found to be more effective and desirable than use of S-turns or decrease in lift-drag ratio through high angle-of-attack flight. In region B the navigational problem was somewhat less routine because of the greater requirements for turning flight; however, particularly with ground vectoring the pilot could successfully complete the initial approach without too much difficulty. Considerably more difficulty was experienced in arriving over a landing site in region C because there is little range margin to compensate for pilot error or for uncertain wind effects.

A number of techniques will be relied on for X-15 navigation during the glide to the base. In normal operations the pilots will be able to complete the mission satisfactorily by following planned procedures with visual cues. The flight operation will be made at a maximum lift-drag ratio ($\alpha = 8^{\circ}$) until the vicinity of the landing site is reached, at which time excess energy will be dissipated through use of speed brakes and circling flight. For emergency operations ground-vectoring techniques may be used to guide the X-15 to high key. In all instances a pilot will be available on the ground to give the required commands. Because of large variations in effective lift-drag ratio due to deceleration and turning flight, ground monitoring of altitude and velocity in addition to X-Y position will be required. Various techniques are currently being evaluated on the simulator and in flight with the F-104A airplane to develop procedures for different flight regimes and situations. In addition, experience will be obtained during X-15 buildup flights which should serve to improve the ground-vectoring methods.

GENERAL FINAL-APPROACH AND LANDING STUDIES

During the past several years a number of programs have been conducted at the NASA Flight Research Center to study various facets of the approach and landing problems at low lift-drag ratio. The landings were made on a concrete runway. Figure 3 shows representative landing patterns of two low-lift-drag-ratio test beds. By suitable scheduling of thrust- and drag-producing devices a value of $(L/D)_{max}$ as low as 2.8 was obtained with the F-104A airplane at a wing loading of about 75 pounds per square foot (ref. 1). A similar procedure enabled investigation of a maximum lift-drag ratio as low as 3.8 with the F-102A at a wing loading of about 35 pounds per square foot (ref. 2). In both investigations circular landing patterns were used by the pilots. A 270° approach over the touchdown point was generally preferred by the pilots, inasmuch as this enabled them to establish a desired initial orientation prior to turning. In the case of the F-104A, after several buildup flights, landings made at a lift-drag ratio above 3.5 were straightforward and not particularly demanding on piloting technique. In figure 3 for the landing in which $(L/D)_{max} = 2.8$, although the pattern was steep and tight, arriving at the desired touchdown point presented no particular problems. The main problem was that of judging the factors controlling the flare to achieve acceptable vertical velocity at touchdown. Although this velocity was always less than 2 feet per second, it was believed that the flare with $(L/D)_{max} = 2.8$ was too demanding for flare technique to be left completely to pilot discretion.

Even at the lowest lift-drag ratio attained in the F-102A, pilot comments indicated that the entire operation including the flare was acceptable. The pilots believed that the lower speeds associated with the lower wing loading of the F-102A made the landing approach easier than did a similar lift-drag ratio with the F-104A.

More recently, another landing technique applicable to gliders with low lift-drag ratios has been developed and demonstrated in flight tests at the Ames Research Center (ref. 3). The technique was designed to simplify the landing procedure of gliders with low lift-drag ratios by explicitly defining the approach flight path required to position precisely the aircraft at the approach end of the runway and by specifying a procedure for programing the flare. Figure 4 shows the various phases of the straight-in approach and flare technique. The initial phase (phase I) of the pattern is a constant-attitude, high-speed dive from altitude aimed at a ground reference point short of the runway threshold. At a specified altitude and speed, a constant g pullout (phase II) is made to a shallow flight path (phase III) along which the airplane decelerates to the touchdown point.

During much of the investigation of reference 3, an F-104A airplane was used as the test bed. Phase I of this landing pattern was entered from an indicated airspeed corresponding to the maximum lift-drag ratio (about 240 knots) at altitudes between 15,000 and 25,000 feet. The pilot then increased the airspeed to that desired at the pull-out. Speeds from 340 to 450 knots and corresponding rates of sink from 150 to 300 feet per second were successfully used in phase I for a configuration having a value of $(L/D)_{max}$ of 4.0, and a speed of about 300 knots was used for a high-drag configuration having a value of $(L/D)_{max}$ of 2.8. Forty-five approaches at low values of L/D were made to an 8,000-foot runway, with reported touchdown-point and airspeed variations of ±600 feet and ±10 knots, respectively.

In order to provide an optimum landing technique for the X-15 and also to obtain information applicable to other reentry vehicles, a program was conducted at the NASA Flight Research Center with several F-104A airplanes to evaluate circular and straight-in approach procedures under simulated X-15 mission conditions. Six of the eight NASA, Air Force, and Navy pilots participating in the program were designated X-15 pilots. For both the circular and straight-in approach techniques the initial heading of the airplane was usually 90° to the runway. Prior to entering the pattern, the pilot set idle power and used full speed brakes; this procedure produced a value of $(L/D)_{max}$ of approximately 4. For the straight-in approach a speed of 350 knots was required at the flare-initiation altitude of 2,200 feet with an aim point 10,000 feet from touchdown. The programed normal acceleration during the flare was 1.4. Flaps and gear were put down after completion of the flare. For comparative purposes, the pilots also performed conventional 270° patterns at indicated airspeeds from 275 to 300 knots with the same configuration sequence as that for the straight-in approach. During most of the tests, the pilot attempted to touch down as close as possible to a prescribed line on the runway at a speed between 180 to 190 knots and with low vertical velocity.

The experienced test pilots liked the flexibility of the circular pattern, in that it allowed them to exercise judgment by taking advantage of pattern variable geometry. This enabled the pilots to continually monitor and correct for unknowns, such as variable winds, and, thus, provide the desired flare-initiation conditions.

The pilots were well aware of the apparent simplicity of the straight-in approach, but they did encounter situations in maneuvering from arbitrary initial conditions of altitude and heading that they felt might be less conducive to corrective action than was afforded by the conventional 270° pattern. Pilots were particularly apprehensive about effects of wind and errors in judgment that would lead to landing short of the intended touchdown point. The pilots were all favorably impressed, however, by the control of the flare provided by the straight-in procedure. Since the pattern is composed of straight-line elements, it is particularly compatible with practical schemes of electronic guidance or automatic control. It should be pointed out that speed brakes were not used to control flight-path angle and that the use of partial speed brakes as a modulating base would afford an effective way of compensating for some of the aforementioned factors that might impede space positioning during a straight-in approach.

In regard to final control of touchdown conditions, there seemed to be little difference between the two landing techniques and, in either case, winds could cause the desired touchdown point to be off 2,500 feet or more. Although successive landings enabled the pilot to partially compensate for wind by variations in technique, it is thought that ±1,000 feet might be a realistic figure for control of the touchdown point under favorable practical operating conditions.

In general, most pilots thought that each technique had features that might prove desirable in the recovery operations of reentry gliders, but no pronounced preference of one technique over the other existed. More important, it appears that a good background of methods and experience are available from which to determine the optimum final approach and landing procedure of reentry vehicles, depending on specific mission requirements and vehicle characteristics. As a result of this program, pilots will probably use a composite technique for the X-15 which they feel combines the best features of both methods. This composite technique will involve a circular approach made slightly in excess of

300 knots and flown so that the pilot will have maximum altitude in the final straight-in leg to follow predetermined flare-control procedures.

X-15 APPROACH AND LANDING EXPERIENCE

General flight studies of test beds with low lift-drag ratios, such as those previously discussed, have made possible assessments of low L/D approach and landing problems. It should be remembered, however, that such studies are still only a form of simulation, in that the pilot at his discretion can apply power and wave-off. Landings for the X-15, on the other hand, are made for the first time in an L/D range from 3 to 4 under actual operational conditions. Figure 5 shows a comparison of the landing lift-drag ratio used in previous research gliders with that of the X-15. In the X-15 operations the pilot delays putting the flap and gear down until he is rather close to the ground. In this manner, the flare is essentially completed in an L/D range similar to that of the X-1E airplane.

Thus far, the X-15 landings have incorporated a 360° or 270° pattern over the touchdown point or a modified S-pattern. The patterns have been generally comfortable and there has been no indication of difficulty due to space positioning.

Figure 6 summarizes the X-15 touchdown conditions in terms of vertical velocity and angle of attack for the first 11 flights. The skid and nose landing-gear combination imposed a rather severe angle-of-attack restriction in the initial flights. This has been somewhat relaxed by landing-gear modifications. The dashed lines represent the present approximate design limits. The four open symbols represent conditions obtained with the original landing-gear configuration; the solid symbols represent landings performed after the gear modifications were made. The touchdown conditions of the first three landings paralleled the original design curve. The fourth landing, however, considerably exceeded the design limits and the airplane suffered major structural damage. The solid symbols indicate that the most recent experience is well within the modified design limits. It is interesting to note that the average X-15 touchdown vertical velocity is of the order of 5 to 6 feet per second as compared with a maximum sink speed at touchdown of $4\frac{1}{2}$ feet per second in all previous research-airplane operations. The reason for this difference is not completely understood but might be due in part to impaired visibility and pilot location relative to the ground prior to touchdown.

Figure 7 presents comparative time histories of the first and fifth landings. In both instances the pitch damper was inoperative. The data presented are angle of attack, stabilizer deflection, indicated airspeed, vertical velocity, and altitude. In the first landing the approach was made at an indicated airspeed of about 270 knots and the flare was started at about 1,200 feet above the terrain. Shortly after the flap deflection was initiated, a severe pitch oscillation is evident; this was probably triggered by the flap trim change. Possibly because he was hindered by this pitch oscillation, the pilot leveled out about 60 feet in the air. The speed continued to bleed off and the mean angle of attack increased to about 10°. The pilot was indeed fortunate to land the vehicle at the bottom of an oscillation and thus avoid major structural damage on the first flight. The control problem on the first flight was undoubtedly the result of a number of factors. The psychological effect of a first flight coupled with a sensitive side-arm controller, lack of pitch-damper augmentation, and control rate limiting all contributed to the control problem. In the fifth landing the pitch damper was also out, but the pilot was more experienced and had been instructed to use the center stick for landing. Flap deflection was initiated at an altitude of only 250 feet, and the landing gear dropped at 20 feet above the ground. This delay in attaining the landing configuration was partially responsible for maintaining a considerably higher forward speed at touchdown than in landing 1. Although the touchdown vertical velocity was about 5 feet per second, the marked reduction in oscillations and angle of attack clearly indicated that landing 5 was a much more desirable landing.

The importance of technique is shown in figure 8. For each of the landings, the center stick was used and the pitch damper was operative. In landing 4 the approach was made at an indicated airspeed of 255 knots, whereas in landing 7 the approach was made at an indicated airspeed of 305 knots. In landing 4 the low speed and gradual flare resulted in an angle of attack of about 11° at touchdown, with a terminal sink speed of 9 feet per second. As stated previously, major structural damage resulted. In landing 7 the pilot performed the flare more abruptly and completed the flare prior to gear and flap deflection. This technique provided 20 seconds of flight below an altitude of 40 feet. The angle of attack at touchdown was about 8°, and final sink speed was only 3 feet per second, well within the design limits.

Landing 7 was considered by the pilots to be one of the best X-15 landings and illustrates the fact that most experienced test pilots appreciate the importance of excess speed near the ground, even though this technique produced significantly higher sink speeds at altitudes above 100 feet.

At present, it is thought that adherence to the NASA recommendation proposed in 1958 of maintaining an approach speed of about 300 knots with flap and gear extension delayed to as low an altitude as possible is providing acceptable X-15 landing characteristics. Furthermore, X-15 pilots believe that use of the F-104A provides an effective means of training for X-15 landing operations.

DEVELOPMENT OF LOW-LIFT-DRAG-RATIO CRITERION

Many interrelated factors must be considered in the development of a practical low-lift-drag-ratio landing criterion. For example, the final approach speed should be subsonic to avoid transonic reduction in lift-drag ratio and to minimize problems of acceleration from best lift-drag-ratio cruise speed. Also, the higher the speed and flight-path angle, the more difficult entry into the pattern is likely to become. Such characteristics also produce larger speed loss during the flare maneuver; therefore, the excess speed available following such high-speed flares is not nearly as large as might be expected. The flare normal acceleration should not exceed 3g and preferably should not be much greater than 2g. A reasonable time should be available after flare completion to make final flight-path corrections prior to touchdown. Finally, the minimum landing speed may well be determined by angle-of-attack restrictions imposed by landing-gear design or vehicle control characteristics.

Systematic studies have been made with representative reentry configurations to study the relative importance of the various factors controlling piloted landings at low lift-drag ratios. Figure 9 presents the results of one such analysis. Calculations were made for a series of 60° to 70° delta-wing configurations having a wing loading of 35 pounds per square foot. A 1.5g to 2g flare was assumed for all conditions.

A landing analysis was made for configurations having values of $(L/D)_{max}$ shown. For each configuration, landing calculations were made for a range of approach or flare-initiation speeds. It was assumed that an angle-of-attack restriction of 13° existed. This angle-of-attack restriction limited the landing speed to greater than 140 knots. The lines on the right side of the figure define flight-path angle as a function of approach speed for the several configurations. The curved lines on the left represent time remaining to decelerate to minimum landing speed following the completion of the flare. The conditions from which acceptable piloted landings might be made were estimated on the basis of the interrelated factors previously mentioned. The area for acceptable flare-initiation speed is bounded on the high-speed side by $\gamma_0 = -35^\circ$ to -45° and is defined on the low-speed side by a minimum time of approximately 5 seconds to terminate the landing following completion of the flare. Although figure 9 is not exactly applicable, note that there are flight tests for the F-102A at a value of $(L/D)_{max}$ of 3.8 at speeds near 200 knots, and the pilots rated the overall characteristics good. Also, based on previous flight studies, this good region should exist for a considerable range of speed. It is at once apparent that a combination of relatively low wing loading and high drag severely limits the attainable approach speeds. For the configurations shown, it is estimated that the lowest value of $(L/D)_{max}$ at flare initiation from which a piloted landing would be feasible is of the order of 2.5.

As has been previously pointed out, pilots prefer vehicles having lower wing loadings for general landing operations at moderately low L/D. However, it has been found from similar studies that the lower marginal level is relatively unaffected by changes in wing loading.

CONCLUDING REMARKS

The range capabilities have been defined and techniques applicable during the initial approach phase of the recovery of lifting hypervelocity vehicles have been described.

In regard to the final approach and landing phase, the more conventional circular pattern and the straight-in approach both have merits that are appreciated by the pilots. The conventional pattern affords somewhat more flexibility of operation in space positioning prior to the flare, whereas the straight-in approach has the advantage of alleviating pilot-judgment requirements during the flare.

Although there have been a number of problems encountered in X-15 landing operations, the present procedure of a relatively high-speed, circular approach with gear and flap extension delayed until completion of the flare is providing entirely satisfactory landings.

Vehicles that should have landing characteristics similar to many of the possible future lifting reentry vehicles have been flight tested. In general, a usable lift-drag ratio of 3.5 or higher should provide the pilot with fair-to-good landing characteristics and allow a speed flexibility that lends itself to a choice of techniques.

There is reason to believe that, regardless of technique, a lift-drag ratio of approximatley 2.5 in the flare may represent a practical lower limit for piloted flared landings.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., April 12, 1960.

REFERENCES

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2. Matranga, Gene J., and Menard, Joseph A.: Approach and Landing Investigation at Lift-Drag Ratios of 3 to 4 Utilizing a Delta-Wing Interceptor Airplane. NASA TM X-125, 1959.

3. Bray, Richard S., Drinkwater, Fred J., III, and White, Maurice D.: A Flight Study of a Power-Off Landing Technique Applicable to Re-Entry Vehicles. NASA TN D-323, 1960.

ILLUSTRATION OF RECOVERY PROBLEM

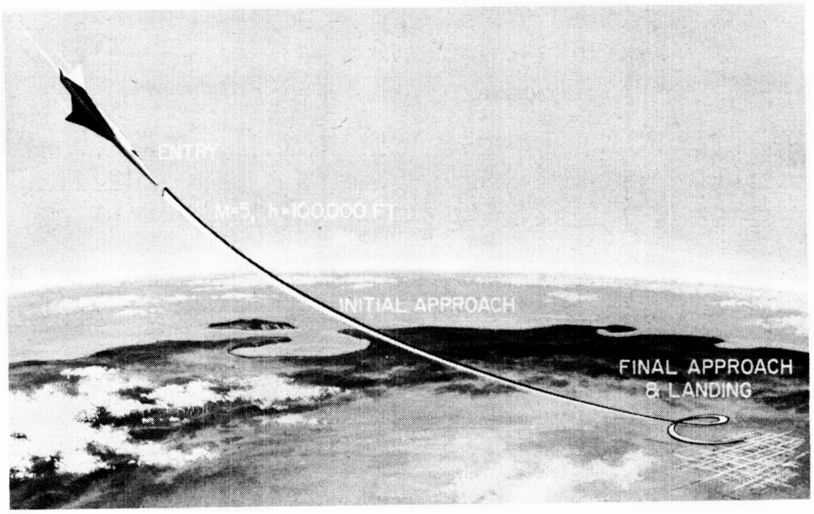

Figure 1 L-60-2491

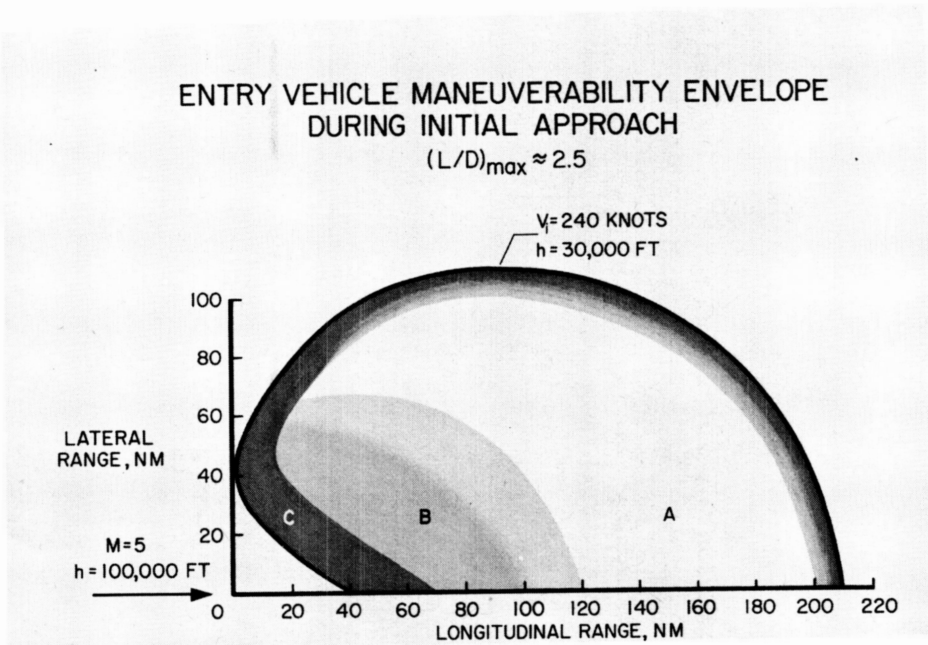

Figure 2 L-60-2492

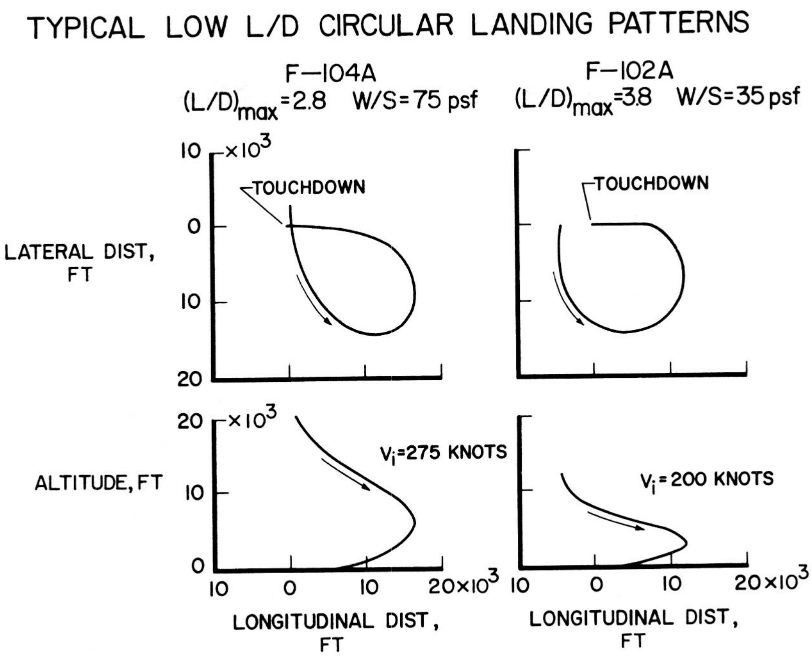

Figure 3

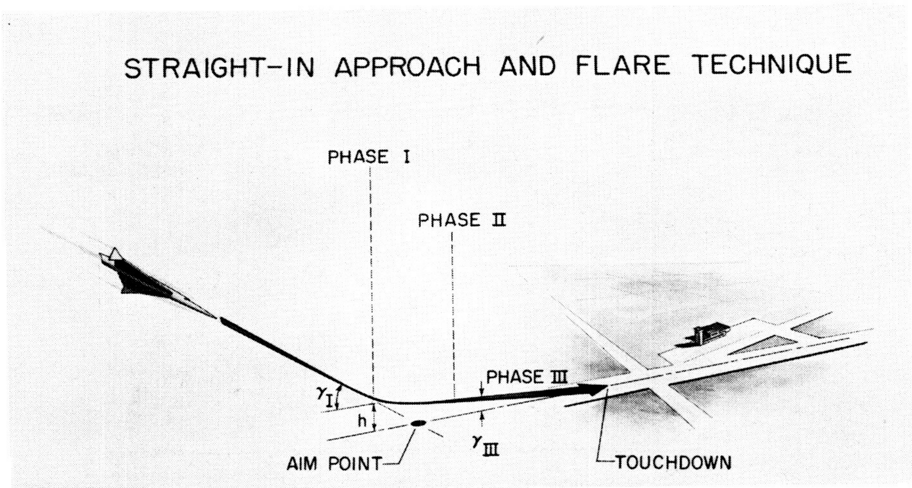

Figure 4 L-60-2493

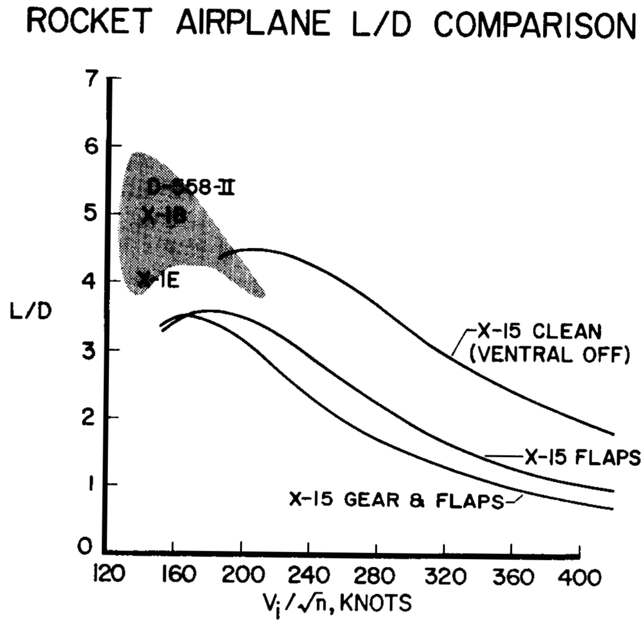

Figure 5

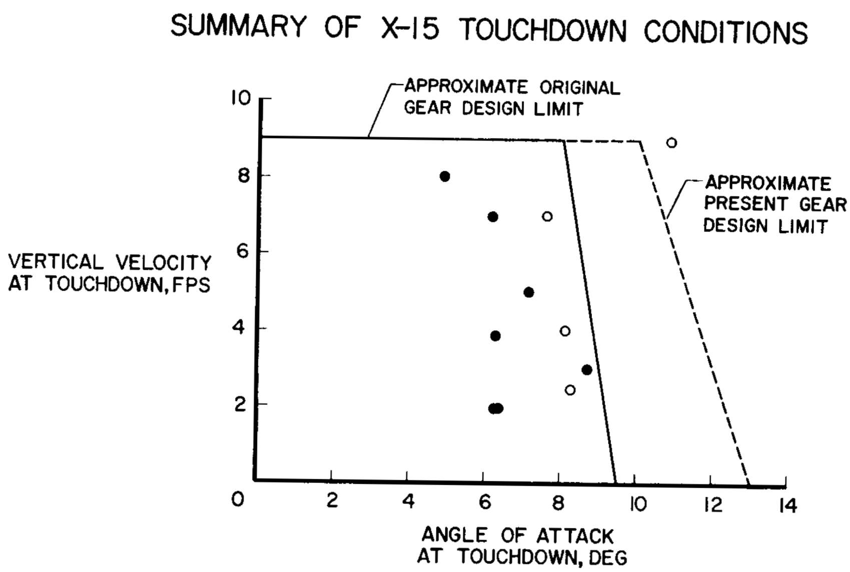

Figure 6

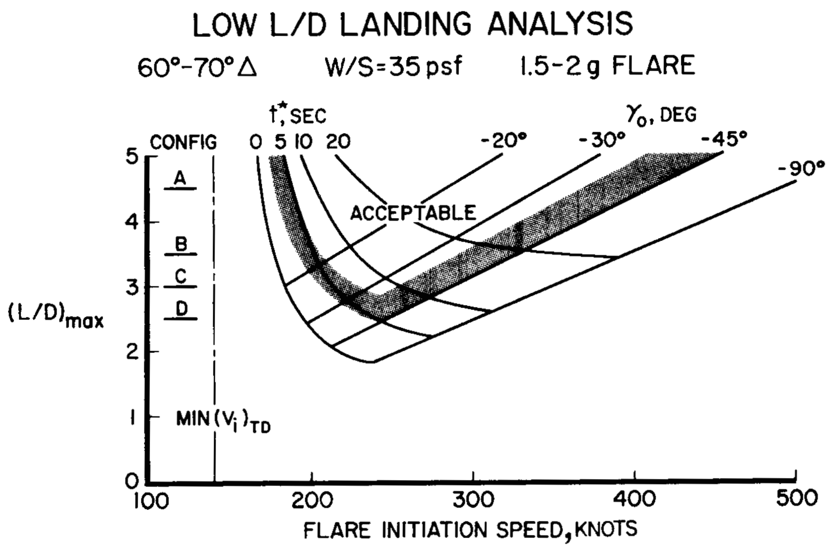

Figure 9

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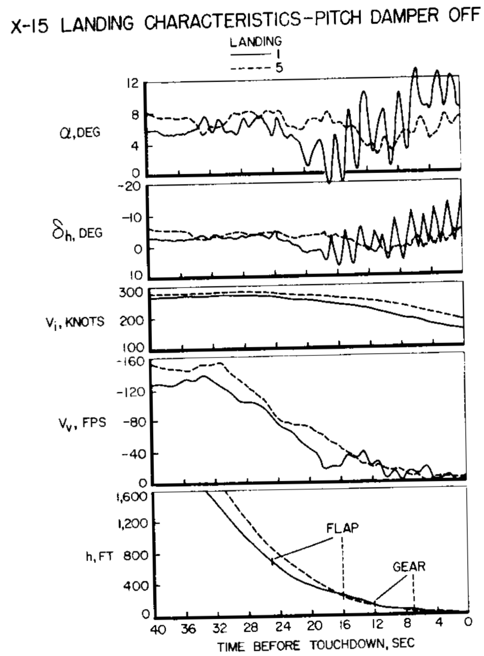

Figure 7

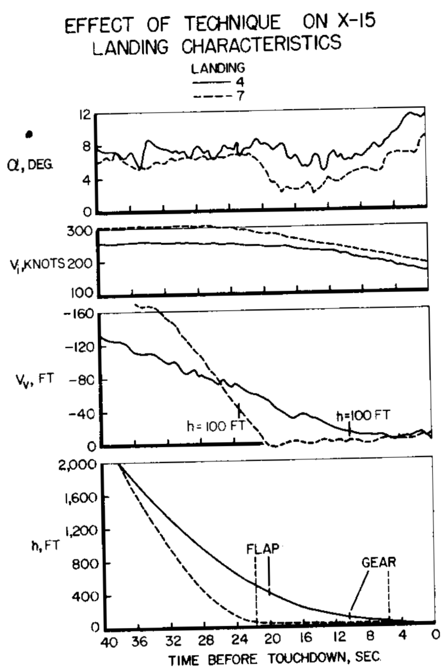

Figure 8